<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>Molecular adhesion controlled microelectromechanical memory device for harsh environment data storage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Chua, Geng Li; Singh, Pushpapraj; Soon, Bo Woon; Liang, Ying Shun; Jayaraman, Karthik Gopal; Kim, Tony Tae-Hyoung; Singh, Navab</td>
</tr>
<tr>
<td><strong>Date</strong></td>
<td>2014-09-15</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/39210">http://hdl.handle.net/10220/39210</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>© 2014 American Institute of Physics (AIP). This paper was published in Applied Physics Letters and is made available as an electronic reprint (preprint) with permission of American Institute of Physics (AIP). The published version is available at: [<a href="http://dx.doi.org/10.1063/1.4895578">http://dx.doi.org/10.1063/1.4895578</a>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.</td>
</tr>
</tbody>
</table>
Molecular adhesion controlled microelectromechanical memory device for harsh environment data storage

Geng Li Chua, Pushpapraj Singh, Bo Woon Soon, Ying Shun Liang, Karthik Gopal Jayaraman, Tony T.-H. Kim, and Navab Singh

Citation: Applied Physics Letters 105, 113503 (2014); doi: 10.1063/1.4895578
View online: http://dx.doi.org/10.1063/1.4895578
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/105/11?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
An insulating liquid environment for reducing adhesion in a microelectromechanical system

Rough surface adhesion in the presence of capillary condensation

Adhesion energy in nanogap In P/In Ga As microcantilevers

Investigation of capillary adhesion between the microcantilever and the substrate with electronic speckle pattern interferometry

The effect of nanoparticles on rough surface adhesion
Molecular adhesion controlled microelectromechanical memory device for harsh environment data storage

Geng Li Chua,1,a) Pushpapraj Singh,1,a) Bo Woon Soon,1 Ying Shun Liang,2 Karthik Gopal Jayaraman,3 Tony T.-H. Kim,3 and Navab Singh1

1Institute of Microelectronics, A*STAR (Agency for Science, Technology and Research), Singapore
2Data Storage Institute, A*STAR (Agency for Science, Technology and Research), Singapore
3School of Electrical & Electronic Engineering, Nanyang Technological University, Singapore

(Received 24 June 2014; accepted 29 August 2014; published online 15 September 2014)

This work demonstrates a cantilever based electrostatic microelectromechanical system device operating as a memory element. Volatile and non-volatile functions are engineered by manipulating molecular adhesion force through contact dimples and restoring force using the cantilever design. For non-volatile RESET operation, a method of detaching the cantilever with 3 V pulsating DC signal at 1 MHz is proposed. SET/RESET cycles are performed up to $10^3$ times at 300 °C without any performance degradation. A writing speed of up to 0.94 μs is achieved, which is faster than conventional high temperature flash memories. With demonstrated attributes, the fabricated device offers excellent potential for harsh environment data storage applications. © 2014 AIP Publishing LLC.

FLASH memory is the mainstream technology for NVM, while other emerging NVM technologies include Resistive RAM (R-RAM), Magnetic RAM (M-RAM) and Phase-Change RAM (PCRAM). The aforementioned NVMs are prone to data loss at higher temperatures (>100 °C).1–3 Microelectromechanical systems (MEMS) devices are known to work in harsh environment (extreme temperature/radiation/vibration). Recently, high temperature non-volatile memory operations have been demonstrated using anchored cantilever and teeter-totter MEMS switches.4,5 The data retention was obtained through van der Waals force5 holding the actuated switch to the contact electrode. Although, desired properties were obtained, both the cantilever and teeter-totter devices used additional electrodes to perform the memory RESET operation.

This letter presents a memory device which uses precisely controlled molecular adhesion force for data retention and method for RESET operation. The presented RESET operation does not require additional electrode and thus saves significant area in device design. The precise control of the molecular adhesion force is achieved by manipulating the total contact area of the cantilever using sub-micron size contact dimples. Volatile and non-volatile memory operations are demonstrated up to 300 °C.

The memory operation is performed on vertically-movable cantilever structure by electrostatic force. Under the applied electrostatic force, the cantilever bent down and touches the contact pad. The cantilever remains in contact position till electrostatic and molecular adhesion force together are higher than the cantilever restoring force. When the electrostatic force is removed and molecular adhesion force is lower than the cantilever restoring force, the cantilever returns to non-contact position and the device operates like a volatile memory. However, with the increase in the cantilever contact area, the molecular adhesion force

overcomes the cantilever restoring force and the cantilever remains in contact with the pad and device operates like a non-volatile memory.

The cantilever is detached from the contact pad by applying a chain of DC voltage pulses to the contact terminal. The pulse based detachment mechanism allows single electrode to execute SET/RESET operation and offers a significant advantage in reducing device footprint compared to the double sided electrode structure.3 Molybdenum (Mo) is chosen due to its high melting point (2610 °C), robustness, small wear out, and good thermal conductivity.7,8 Theoretical formulation is employed to design the volatility and non-volatility function of the memory devices explained in the next paragraph. The experimental results confirm that the molecular adhesion force can be leveraged to develop power efficient MEMS memory (volatile and non-volatile) devices.

The MEMS memory devices consist of three terminals (gate, source, and drain) as shown in Fig. 1(a). The movable cantilever (source electrode) is positioned above the actuation (gate electrode) and the contact (drain electrode) pads. When a potential (greater than cantilever’s pull-in voltage) is applied between the source and gate electrodes, the cantilever pulls in to the contact pad. The gate electrode is covered by 50 nm thick aluminum oxide ($\text{Al}_2\text{O}_3$) to prevent the cantilever from touching the gate during the pull-in operation. It is assumed that the contact between the source and drain is ohmic due to the pure Mo electrodes. To study the molecular adhesion force effects on the volatility of the MEMS devices, various square dimple structures (contact) are designed at the cantilever’s tip as shown in Figs. 1(b) and 1(c). The size of each square dimple is 500 nm × 500 nm. Four kinds of devices (M1 ~ M4) are designed and their dimensional parameters are summarized in Table 1. The parameters are cantilever width ($w$), actuation length ($W$), cantilever length ($L$), cantilever thickness ($h$), actuation gap ($d_0$), and the number of dimples.

The device operation (SET/RESET) is determined by the combination of three forces (electrostatic forces, molecular
adhesion forces and restoring forces). The molecular adhesion force between the metal contacts is proportional to the number of dimples. To implement volatile operation, the cantilever is designed to have high restoring force and low molecular adhesion force while low restoring and high molecular adhesion force are employed for non-volatile operation. Cantilevers with high restoring force and low molecular adhesion force are designed with relatively shorter cantilever lengths and with fewer dimples (M1 and M2 in Table I). Decreasing the cantilever length increases the restoring force and reducing the number of dimples reduces the molecular adhesion forces. Conversely, device M3 and M4 are designed with longer beam lengths to reduce the cantilever restoring force and more dimples to increase the molecular adhesion force. By controlling the number of dimples and the cantilever length, the proposed MEMS memory devices exhibit either volatile or non-volatile characteristics. As described earlier, the three forces determine the memory phenomenon for MEMS cantilever device, and the operation principle is illustrated in Fig. 2.

The electrostatic force is determined by the standard parallel plate capacitor theory

$$F_{electric} = \frac{1}{2} \frac{\varepsilon_0 W w V^2}{d^2},$$  \hspace{1cm} (1)

where $W$ represents the gate length, $w$ is the cantilever width, $d$ indicates the bent cantilever gap from the bottom electrode, $\varepsilon_0$ is the vacuum permittivity, and $V$ is the applied bias. The fringing field effect of the device is assumed to be negligible.

The mechanical bending of the cantilever follows the conventional spring force $F = k(x)$, which is exponentially proportional to the cantilever’s deflection. The cantilever restoring force is expressed by the following equation:

$$F_{spr} = k(d_0 - d),$$  \hspace{1cm} (2)

where $E$ represents the Young’s Modulus of the cantilever, $h$ is the cantilever’s thickness, $w$ is the beam width and $d_0$ the original cantilever’s gap distance.\(^9,10\)

The analytical model of the adhesion force was reported to be dependent on the surface roughness.\(^6\) The molecular adhesion force ($F_{adh}$) and the adhesion energy ($\Gamma$) can be written as follows:

### Table I. The cantilever design parameters for device M1 to M4 are as summarized.

<table>
<thead>
<tr>
<th>Device type</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$ ($\mu$m)</td>
<td>2</td>
<td>2</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>$W$ ($\mu$m)</td>
<td>13.5</td>
<td>14</td>
<td>23</td>
<td>31</td>
</tr>
<tr>
<td>$L$ ($\mu$m)</td>
<td>18</td>
<td>19</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>$h$ ($\mu$m)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$d_0$ ($\mu$m)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Dimple No.</td>
<td>9</td>
<td></td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 1. An illustration of the cantilever device with (a) the top view, (b) the cross section view of non-volatile memory device with 25 (5 $\times$ 5) dimples and (c) the cross section view of volatile memory device with 9 (3 $\times$ 3) dimples.

FIG. 2. Major forces are electrostatic, restoring and adhesion. (a) Electrostatic force is applied at gate terminal. (b) Source makes contact with drain under the electrostatic force. (c) Non-volatility: Source remains in contact with drain when the electrostatic force is removed and molecular adhesion force is larger than cantilever restoring force. (d) Volatility: Source deactuates when cantilever restoring force is larger than molecular adhesion force.
This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 155.69.4.4
On: Tue, 22 Dec 2015 07:28:23

\[ F_{adh} = \frac{2\Gamma A}{d_{adh}}, \]  
\[ \Gamma = \frac{A_{Hamaker}}{12\pi D_{rms}}, \]

where \( A \) is the contact area, \( d_{adh} \) is the van der Waals distance, \( D_{rms} \) is the root mean square surface roughness of Mo, \( \alpha \) is the correction function,\(^3,11\) and \( A_{Hamaker} \) \((16.2-45.5 \times 10^{-20} \text{J})\) is the Hamaker constant for metal.\(^12,13\) The surface roughness \( D_{rms} \) was extracted from atomic force microscopy (AFM) scan.

The cantilever pull-in voltage is obtained by equating the electrostatic force (\( F_{elec} \)) and cantilever restoring force (\( F_{spr} \)). It was reported that abrupt switching occurs when a cantilever is bent to less than two third of its original gap distance and \( F_{elec} \) is larger than \( F_{spr} \).\(^4\) The pull-in voltage (when \( L = W \)) is expressed by the following equation:

\[ V_p = \sqrt{\frac{2\varepsilon_0 W^4}{8.37d^0 W^4} \left( 5 - \frac{0.19}{d^0_{w} W^{.75}} - \frac{0.19}{d^0_{l} W^{.75}} + \frac{0.4h^{0.5}}{d^0_{b} W^{.75}} \right)}. \]

In the designed devices (M1-M4), the most critical parameter contributing to the pull-in voltage variation is the cantilever length. Also, it was theoretically reported that with all parameters (\( h, d, \) and \( w \)) kept constant, pull-in voltage (\( V_p \)) increases significantly by reducing the cantilever length.\(^9\) Similar relation could be observed for cantilever restoring force (\( F_{spr} \)) as given in Eq. (2), where \( F_{spr} \) decreases when cantilever length increases. Longer beams (M3 and M4) result in lower \( V_p \) and \( F_{spr} \) compared to shorter beams (M1 and M2) containing higher \( V_p \) and \( F_{spr} \). Therefore, longer beams (M3 and M4) are designed to demonstrate non-volatility, whereas shorter beams (M1 and M2) exhibit volatile functionality.

The cantilever device was fabricated on 8 in. silicon wafers. PECVD silicon nitride (Si\(_3\)N\(_4\)) and ALD aluminum oxide (Al\(_2\)O\(_3\)) were deposited for dielectric isolation. PVD Mo was deposited and patterned to form the bottom gate and the contact pad electrodes. 50 nm Al\(_2\)O\(_3\) was deposited and patterned for electrical isolation of the gate electrode. Sacrificial PECVD SiO\(_2\) was then deposited and planarized by CMP to eliminate topography. The contact dimples were patterned on the SiO\(_2\) surface and etched to stop on Mo. Thin layer of SiO\(_2\) was again deposited before patterning and etching SiO\(_2\) to create the cantilever’s anchor. PVD Mo was then deposited and patterned to form cantilever electrode. The device was finally placed in VHF to remove the sacrificial SiO\(_2\).

SEM images of the suspended cantilever and contact structures are shown in Fig. 3(a). The cantilever is designed with the length and width of 30 \( \mu \text{m} \) and 2.5 \( \mu \text{m} \), respectively. The designed air gap between the cantilever and the bottom electrode was 500 nm with 25 (5 \( \times \) 5) contact dimples at the tip of the cantilever for devices M3 and M4 as shown in Fig. 3(b). Fig. 3(c) shows the tip of M1 and M2 devices with 9 (3 \( \times \) 3) dimples. The surface roughness of Mo is extracted from atomic force microscopy (AFM) using Veeco dimension 5000 and the measured \( D_{rms} \) of 2.878 nm is as shown in Fig. 4. The required value of \( D_{rms} \) for achieving the adhesion energy of \( \Gamma = 0.986 \text{ mJ/m}^2 \) is calculated by Eq. (5). This corresponds to the molecular adhesion force of 0.171 \( \mu \text{N} \) for each dimple as described in Eq. (4) with \( d_{adh} = D_{rms} \) and \( \alpha = 0.1 \).\(^3,16\) As a result, the implemented 9 and 25 dimples generate the molecular adhesion force of 1.15 \( \mu \text{N} \) and 0.43 \( \mu \text{N} \), respectively.

The pull-in voltage measurement results for volatile (device M1) and non-volatile (device M3) memories are illustrated in Fig. 5. \( I/V \) measurement are conducted at 25 \( ^\circ \text{C} \), 150 \( ^\circ \text{C} \), and 300 \( ^\circ \text{C} \). As expected, pull-in voltage is found to decrease with increase in temperatures. For device M1, Fig. 5(a) shows the pull-in voltage of 10.34 V \( (300 \; \text{C}) \), 10.89 V \( (150 \; \text{C}) \), and 11.38 V \( (25 \; \text{C}) \). The pull-out voltages are observed to be 7.37 V \( (300 \; \text{C}) \), 6.82 V \( (150 \; \text{C}) \), and 6.55 V \( (25 \; \text{C}) \). The pull-in voltages of device M3 are observed to be 11.52 V \( (300 \; \text{C}) \), 13.47 V \( (150 \; \text{C}) \), and 14.84 V \( (25 \; \text{C}) \).
13.81 V (25 °C) as shown in Fig. 5(b). There is no pull-out observed after removing the actuation voltage, and it confirms the non-volatility for the device M3.

After performing the SET operation on the non-volatile memory devices (M3 and M4), the cantilever release (RESET) operation is performed by a vibrational release technique. From the experiment, square pulses of 1 MHz with 3 V in amplitude are applied to the drain electrode while the gate/source electrodes are connected to ground terminal. The applied pulses pull down the cantilever at short intervals and eventually lead the cantilever to vibrate. The amplitude of pulses is kept smaller than the cantilever pull-in voltage to avoid the pull-in condition. The vibration amplitude gradually grows by applying suitable voltage pulses close to the resonance frequency of the cantilever. The increasing vibrational force together with the cantilever restoring force eventually overcomes the molecular adhesion force, and brings back the cantilever to its unstuck position. Although the actuation electrode controlled cantilever RESET theory was reported earlier, the contact electrode based cantilever detachment proposed in this work is reported and needs further investigation to validate the accurate mechanism.

Fig. 6 illustrates the SET/RESET cycling behavior of volatile memory (device M1) at 300 °C. The SET/RESET operation is performed for 10^5 cycles and measured with semiconductor device analyzer. An input pulse (V_G, pulse) is applied at gate electrode as shown in Fig. 6(a) and the current output response is observed at drain electrode as shown in Fig. 6(b). The SET operation on device M1 is performed by applying 12 V pulse for 1 ms duration. It is then followed with RESET operation by applying 0 V pulse for subsequent 1 ms. Furthermore, the switching time is experimentally measured to determine the SET response speed of device M1 at 25 °C, 150 °C, and 300 °C. Tektronix AFG3102 dual channel arbitrary/function generator is used to generate actuation pulses at gate electrode, and output signal is observed at drain electrode. All the signals are collected and time delay is recorded by Tektronix DPO7054 Digital Phosphor Oscilloscope. Fig. 6(c) shows the switching time of 0.94 μs measured at 300 °C. At 150 °C, the switching time slows down to 1.63 μs and further to 2.31 μs at 25 °C.

The summary of the volatile and non-volatile memories is presented in Fig. 8. Based on molecular adhesion force (F_{adh}) and cantilever restoring force (F_{spr}), the gradient line...
separates the graph into two, with adhesion force dominant at upper portion of the graph and restoring force dominant at the lower portion of the graph. Non-volatile memory (M1 and M2) lies in the adhesion force dominant region and the volatile memory (M3 and M4) in the restoring force dominant region. The error bar (vertical line along the middle point of each device) plotted represents the error contributed by the Hamaker constant of metal in the range of 16.2–45.5 × 10^{-20} J.

This paper demonstrated MEMS volatile and non-volatile memory devices through precise control of molecular adhesion force and cantilever restoring force. I/V, SET/RESET cycling, and switching speed characterization results were obtained at ambient (25°C) to high temperatures (150°C, 300°C). The devices have demonstrated the SET and RESET operations up to 10^3 times at 300°C. The response time of 0.94 μs was observed at 300°C for volatile memory device. The non-volatile memory device showed the response time of 0.95 μs. The cantilever detachment was demonstrated through applying reset pulses at contact electrode. This offers potential RESET phenomenon not only for the proposed MEMS memory devices but also for many other MEMS actuators.

This work was supported by Institute of Microelectronics, Agency of Science, Technology and Research Singapore (A*STAR), Singapore, in collaboration with Nanyang Technological University of Singapore. Authors are grateful to Dr. Vincent Pott for the contribution and guidance in the research works.